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LOGIC AND EQUATIONS FOR RTCC COMPUTATION OF LUNAR LANDING DESCENT TRAJECTORY

By Edwin G. Dupnick,
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PROJECT APOLLO

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By Edwin G. Dupnick

SUMMARY

This report defines the Real-Time Computer Complex (RTCC) logic required to simulate the powered lunar landing descent trajectory and supersedes reference 1 due to changes in reference 2. The equations provided in this document should produce an acceleration profile that will match the one produced by the onboard equations. Flow charts, symbol glossary, and required input parameters and values (if available) are presented.

DESCRIPTION OF DESCENT PHASES

Although the powered descent maneuver is one long continuous burn (about 12 minutes), it can be divided into five operational phases, each with its own steering-guidance logic and associated targets. The following table shows the pertinent information for each phase.

Phase no.	Phase name	Required steering	Required targets[a]
-2	Preignition	Quadratic	$\overline{RDG}_o$, $\overline{VDG}_o$, $\overline{ADG}_o$, $\overline{JDG}_o$
-1	Ullage and trim	Attitude hold	None
0	Braking	Quadratic (linear last 20 sec)	$\overline{RDG}_o$, $\overline{VDG}_o$, $\overline{ADG}_o$, $\overline{JDG}_o$
1	Approach	Quadratic (linear last 10 sec)	$\overline{RDG}_1$, $\overline{VDG}_1$, $\overline{ADG}_1$, $\overline{JDG}_1$
2	Vertical descent	Velocity following	$\overline{VDG}_2$

[a]The subscripts are used only to indicate three distinct target sets.

All targets are to be achieved in the guidance coordinate system (GCS) and are defined as follows:

$\overline{RDG}$ = desired terminal radius vector

$\overline{VDG}$ = desired terminal velocity vector

$\overline{ADG}$ = desired terminal acceleration vector

$\overline{JDG}$ = desired terminal jerk (first time derivative of acceleration) vector

The actual target values are contained in table II and taken from reference 3.

Preignition

The first phase (phase-2), preignition phase, determines the time to begin ullage and the unit thrust vector direction to be maintained throughout the ullage and trim phase. Ullage initiation time is determined (actually braking phase initiation time) so that the down range component of the LM position will be equal to a preselected ignition value neglecting the ullage and trim phase thrusting. This value has been selected so that the descent propulsion system (DPS) will throttle down and throttle control will be regained about 118 seconds prior to braking phase termination. Correction terms are included to account for deviations in spacecraft altitude, speed, and lunar landing site out-of-plane distance following the descent orbit injection (DOI) maneuver.

The preignition phase (flow chart I) can be simulated by the following steps.

Integrate the spacecraft trajectory in free flight ahead to the predicted time of braking phase initiation. If the solution to the preignition computation routine is considered to be unsatisfactory, a new state vector is requested by specifying a new predicted braking phase initiation time. Upon determining a successful solution, the state vector should be returned to the original conditions or to some arbitrary time not less than 2 seconds prior to the solved time. The trajectory should then be propagated ahead to the next phase, the ullage and trim, and proper initialization will occur.

Ullage and Trim Phase

The ullage and trim phase (phase-1) is required to settle the DPS propellants for main engine ignition and to minimize the attitude transients at throttle up respectively. The unit thrust vector is inertially fixed during this phase in a direction computed during the preignition phase. However, the magnitude changes at the end of ullage when the DPS engine ignites to begin the trim phase.

Braking Phase

The braking phase (phase 0) reduces the spacecraft relative velocity and lowers the altitude so that visual evaluation of the landing site can be started. Quadratic guidance is used throughout the phase except for the last 20 seconds, during which linear guidance is employed. Normally for most of this phase quadratic guidance commands a thrust magnitude greater than approximately 63 percent of DPS maximum design thrust (10 500 lb) and the DPS engine is held at the fixed throttle point (FTP) (corresponds to about 93% of maximum). When the commanded thrust falls below 57 percent, throttle control is regained and the DPS is throttled to follow the commanded level. Thus the DPS will not throttle up (to FTP), until the commanded thrust exceeds 63 percent of maximum and not throttle down (to whatever is commanded), until less than 57 percent maximum thrust is commanded. This hysteresis loop (57-63%) is an integral part of the DPS throttle control logic. The engine should nominally throttle down in this phase at TGO equal to approximately 118 seconds and remain in the throttleable region throughout the remainder of powered descent. If, however, the commanded thrust level should be greater than 63 percent, the DPS is again brought to the FTP level and held until the commanded thrust once more returns to the throttleable region. This is referred to as a pulse out. During the last 30 seconds of the braking phase and the last 10 seconds of the visibility phase, no DPS pulse outs are permitted. That is, should the commanded thrust level exceed 63%, the thrust level is set to 63% instead of FTP. The spacecraft is always steered along the commanded thrust direction regardless of the thrust level the throttle routine is dictating.

Approach Phase

For the nominal case the approach phase (phase 1) allows a visual assessment of crew safety and of the planned landing area. As in the braking phase, quadratic guidance controls most of this phase and linear guidance is used during the last ten seconds.

Vertical Descent Phase

The vertical descent phase (phase 2) is used to lower the spacecraft at a specified rate from about 75 feet above the lunar surface using the velocity-following guidance. This rate is maintained until the spacecraft center of gravity is about 15 feet above the surface, at which time the LM landing gear pads should touch the lunar surface and the powered landing guidance logic is completed.

COORDINATE SYSTEMS

Only two coordinate systems are required since point mass equations are considered. The spacecraft state vector is maintained in the Platform Coordinate System (PCS) and the GCS is used to calculate the thrust and attitude commands.

The PCS is a right-handed orthogonal coordinate system, with its origin at the center of the moon. The X-axis pierces the nominal landing site at the nominal landing time. The Z-axis is in the CSM orbit plane and points in the direction of CSM travel at the nominal landing time. The Y-axis completes the system.

The GCS is also a right-handed orthogonal coordinate system. Its origin is at the current landing site and therefore the system must be continually updated due to lunar rotation. However, updating is bypassed during linear guidance (the last 20 seconds of braking phase and the last 10 seconds of approach phase) and during the vertical descent. The X-axis is upward along the current lunar landing site radius vector. The Y-axis is oriented such that the LM radius, velocity, acceleration, and jerk vectors are all coplanar (in the X-Z plane) when the spacecraft achieves all the current targets or aim conditions. The Y-axis forms a unit normal to the plane defined by the LM radius vector and the lunar landing site at phase termination. The Z-axis completes the system.

The spacecraft targets are defined in terms of the GCS and are invariant in the system. However, they are not invariant in inertial space since the relationship between the GCS and the PCS continually changes as the landing site rotates and changes its position in inertial space.

A third coordinate system, the spacecraft body system (SBS), is introduced briefly in the preignition computation routine. It is a right-handed orthogonal coordinate system coincident with the LM's navigational base system and is used to define the prethrust alignment of the spacecraft. Since it is understood that the RTCC will not compute gimbal angles during the powered landing burn, the SBS need not be used in any other computations.

ENGINE MODEL

The throttle command routine modifies guidance-commanded thrust to account for engine constraints. This logic provides the proper thrust application which is not necessarily the thrust commanded by the guidance. The engine model portion of the throttle command routine provides full thrust as a linear function of time that the DPS has operated at the high thrust setting (ref. 4). Specific impulse is also provided as a linear function of time under high thrust. However, when the engine is being throttled (commanded thrust is less than 57 percent of maximum), the achieved thrust is equal to that which is commanded, and the specific impulse is obtained from a third-order polynominal. These equations will closely approximate DPS engine test results and thus provide realistic thrust and weight histories in the simulation of the powered landing maneuver.

All the symbols used in the flow charts are listed and defined in table I. The required inputs are listed in table II. For ease of assembly all required inputs can be grouped into five categories: state vector input, targeting input, ignition computation input, and performance data input.

TABLE I.- SYMBOLS FOR POWERED LANDING GUIDANCE FLOW CHARTS

Symbol	Definition
$\overline{\text{ACG}}$	Commanded acceleration vector defined in the guidance coordinate system (GCS) including the lunar gravitational acceleration vector.
$\overline{\text{ACP}}$	Commanded acceleration vector defined in the platform coordinate system (PCS) including the lunar gravitational acceleration vector.
$\overline{\text{ADG}}$	Desired current phase terminal acceleration vector to be achieved in the GCS.
AFC	Magnitude of commanded acceleration excluding lunar gravity acceleration.
$\overline{\text{AFCP}}$	Commanded acceleration vector in the PCS excluding the lunar gravity acceleration vector.
DELISP	Change in specific impulse with respect to time from braking phase initiation, of the descent propulsion system (DPS) due to an eroding engine nozzle. Constant, required input.
DELTGO	Change in time-to-go (TGO) necessary to satisfy desired terminal conditions due to advancement of the spacecraft trajectory.
DELTHR	Change in actual thrust with respect to time from braking phase initiation, for the DPS due to an eroding engine nozzle. Constant, required input.
DTC	Criterion value for TGO iteration used to test for satisfactory convergence.
DTTT	Computed change in predicted braking phase initiation time as computed by the preignition computation routine.
FC	Thrust commanded by the guidance equations, unfiltered by the throttle command routine.
FCTH	Actual thrust to be achieved by the DPS as determined by the throttle command routine. Commanded thrust after filtering FC through the throttle command routine.

TABLE I.- SYMBOLS FOR POWERED LANDING
GUIDANCE FLOW CHARTS - Continued

Symbol	Definition
FLAG	A flag word used in aim point routine to monitor TGO for proper selection of targets. 0 preignition 1 targets will be changed or a phase ended or both 2 braking phase, linear guidance initilization 3 visibility phase, linear guidance initilization
FLTH	Throttle boundary flag word used mainly to determine whether the DPS is to be operated in the throttable or maximum throttle setting.
GFLAG	A flagword used in thrust acceleration computation to select the appropriate type of steering logic to be used. 1 linear guidance 2 quadratic guidance 3 velocity-following 4 constant attitude
$\overline{GMP}$	The gravitational acceleration vector of the moon defined in terms of the PCS at the spacecraft.
GOE	Magnitude of gravitational acceleration vector on earth's surface. Constant, required input.
J	Index used in the aim point routine for routing to target conditions for appropriate descent guidance phases. 1 preignition 2 ullage and trim 3 braking

TABLE I.- SYMBOLS FOR POWERED LANDING GUIDANCE FLOW CHARTS - Continued

Symbol	Definition
	4 visibility
	5 vertical descent
$\overline{JDG}$	Desired current phase terminal jerk (first-time derivative of acceleration) to be achieved in the GCS.
$\overline{LP}$	Position vector of the current desired lunar land site defined in terms of the PCS.
LPM	Vector magnitude of the current desired lunar landing site.
NN	Counter used in the TGO computation to determine a nonconvergent TGO situation.
PHASE	Flagword used to identify the various phases of the descent trajectory
	-2 preignition
	-1 ullage and trim
	0 braking
	1 approach
	2 vertical descent
QN	Ignition test quantity used to start the powered braking phase when the downrange component of vehicle position is equal to a preselected ignition value. The quantity also contains correction terms to account for undesirable deviations in altitude, speed, and site out-of-plane distance.
$\overline{RDG}$	Desired current phase position vector to be achieved in the GCS.
$\overline{RG}$	Present spacecraft position vector with respect to the current lunar landing site defined in the GCS.

TABLE I.- SYMBOLS FOR POWERED LANDING

GUIDANCE FLOW CHARTS - Continued

Symbol	Definition
RIGXG	Desired component of the spacecraft position in the X direction of the GCS at braking phase initiation. Constant, required input.
RIGZG	Desired component of the spacecraft position of the Z direction of the GCS at braking phase initiation. Constant, required input.
$\overline{RP}$	Present spacecraft position vector in terms of the PCS. Constant, required input.
TAUG	Time constant used to control rate at which the desired descent velocity is obtained during the vertical descent phase.
TF	Time of current phase termination.
TGO	Time remaining between current time and time of current phase termination.
TG2P	Transformation matrix which converts a vector from the GCS to the PCS.
THPC57	A DPS engine thrust value corresponding to about a fifty-seven percent throttle setting. Constant, required input.
THPC63	A DPS engine thrust value corresponding to about sixty-three percent throttle setting. Constant, required input.
THRMAX	An uneroded DPS engine thrust value corresponding to the maximum throttle setting. Constant, required input.
THRMIN	A DPS engine thrust value corresponding to minimum allowable throttle setting. Constant, required input.
THRTRM	Thrust value used during the trim portion of the ullage and trim phase. Constant, required input.

TABLE I.- SYMBOLS FOR POWERED LANDING GUIDANCE FLOW CHARTS - Continued

Symbol	Definition
THRUL	Thrust value used during the ullage portion of the ullage and trim phase. Constant, required input.
TIME	Current time, required input.
TL	Time at which the radius vector of the desired landing site is defined. Required input.
TOLD	Value of time during the previous pass through the descent logic.
TP2G	Transformation matrix which converts a vector in the PCS to a vector in the GCS. $TP2G = TG2P^T$
TRMISP	Specific impulse of the DPS engine during the trim portion of the ullage and trim phase. Constant, required input.
TRMT	Duration of the trim portion of the ullage and trim phase. Constant, required input.
TTT	Time of braking phase initiation as determined by the preignition computation routine.
TUL	Actual time to begin the ullage prior to DPS ignition as computed by the preignition computation routine.
$\overline{UAFCP}$	Unit thrust vector direction to be held during the ullage and trim phases, as determined by the preignition computation routine.
$\overline{UDXP}$, $\overline{UDYP}$, $\overline{UDZP}$	Desired unit vector orientation of the spacecraft X-, Y-, and Z-body axes, respectively, in the PCS as computed by the preignition computation routine.
ULISP	Specific impulse during the ullage phase. Constant, required input.
$\overline{ULP}$	Unit position vector of the current desired lunar landing site defined in terms of the PCS.

TABLE I.- SYMBOLS FOR POWERED LANDING

GUIDANCE FLOW CHARTS - Continued

Symbol	Definition
UT	Duration of the ullage portion of the ullage and trim phase ignition. Constant, required input.
$\overline{UXGP}$, $\overline{UYGP}$, $\overline{UZGP}$	Unit X, Y, and Z vectors, respectively, of the GCS in terms of the PCS
$\overline{VDG}$	Desired current phase terminal velocity vector to be achieved in the GCS.
VDGM	Magnitude of velocity vector to be achieved during the velocity-following mode in the vertical descent phase. Constant, required input.
$\overline{VG}$	Spacecraft velocity vector with respect to the lunar landing site defined in the GCS.
VIGG	Desired magnitude of spacecraft velocity vector with respect to the lunar landing site at braking phase initiation. Constant, required input.
$\overline{VP}$	Spacecraft inertial velocity vector in terms of the PCS.
WDOT	Propellant flow rate
$\overline{WMP}$	Angular rotation vector of the moon in terms of the PCS. Constant magnitude, required input.
WT	Current spacecraft weight.
$\overline{WXR}$	Difference between the inertial velocity of the spacecraft and the relative velocity (with respect to the moon). Cross product of the angular rotation vector of the moon and the current spacecraft position vector.
$\overline{XAD}$	Desired terminal acceleration vector to be achieved in the GCS. Constant, required input.
XISP	Current specific impulse.

TABLE I.- SYMBOLS FOR POWERED LANDING

GUIDANCE FLOW CHARTS - Concluded

Symbol	Definition
XISP0 XISP1 XISP2 XISP3	Coefficients utilized in the polynominal relating specific impulse to actual thrust. Constants, required input. To be supplied later.
$\overline{XJD}$	Desired terminal jerk vector (first time derivative of acceleration) to be achieved in the GCS. Constant, required input.
XKIG	Coefficient used in the preignition computation routine to increase the rate of convergence for the solution of the braking phase initiation time.
XKISP	Constant term used in the first order polynominal used to simulate the change in specific impulse due to an eroding DPS engine nozzle. Constant, required input.
XKX, XKY, XKV	Coefficients used to scale correction terms due to deviations in spacecraft altitude, landing site out-of-plane distance and speed, respectively, in the computation of braking phase initiation time. Constants, required input.
XM	Current spacecraft mass.
$\overline{XRD}$	Desired terminal radius vector to be achieved in the GCS. Constants, required input.
XTGO	Estimated time durations allotted for the specific phases. Constants, required input.
$\overline{XVD}$	Desired terminal velocity vector to be achieved in the GCS. Constants, required input.

TABLE II.- REQUIRED INPUT

(a) State vector

Symbol	Value	Definition
$\overline{RP}$	--	--
TIME	--	--
$\overline{VP}$	--	--

(b) Targeting

Symbol	Value	Definition
$\overline{LP}$	--	--
TAUG	--	--
TL	--	--
VDGM	-3 fps	--
$\overline{XAD}$		
XAD(1)	-1.696 ft/sec^2	
XAD(2)	0 ft/sec^2	
XAD(3)	-9.453 ft/sec^2	Braking phase targets
XAD(4)	0.05 ft/sec^2	
XAD(5)	0 ft/sec^2	Approach phase targets
XAD(6)	-0.65 ft/sec^2	
$\overline{XJD}$		
XJD(1)	0 ft/sec^3	
XJD(2)	0 ft/sec^3	Braking phase targets
XJD(3)	-0.011885 ft/sec^3	
XJD(4)	0 ft/sec^3	
XJD(5)	0 ft/sec^3	Approach phase targets
XJD(6)	0.034336 ft/sec^3	
$\overline{XRD}$		
XRD(1)	9592 ft	
XRD(2)	0 ft	Braking phase targets
XRD(3)	-33084 ft	
XRD(4)	77.13 ft	
XRD(5)	0 ft	Approach phase targets
XRD(6)	-1.733 ft	

TABLE II.- REQUIRED INPUT - Continued

(b) Targeting - Continued

Symbol	Value	Definition
XTGO		
XTGO(1)	510 sec	Preignition
XTGO(2)	33.5 sec	Ullage and trim
XTGO(3)	510 sec	Braking
XTGO(4)	160 sec	Approach
XTGO(5)	20 sec	Vertical descent
$\overline{XVD}$		
XVD(1)	-158.8 fps	
XVD(2)	0 fps	Braking phase targets
XVD(3)	563.7 fps	
XVD(4)	-3.1 fps	
XVD(5)	0 fps	Approach phase targets
XVD(6)	1.3 fps	

(c) Ignition computation

RIGXG	-130822.38 ft	
RIG2G	-1437487.9 ft	
VIGG	5574 fps	
XKIG	1.0	
XKX	0.617631 ft/ft	
XKY	$7.55194392 \times 10^{-7}$ ft/ft^2	
XKV	411.41232 ft/fps	

(d) Lunar constants

$\overline{WMP}$	--	--
$\overline{GMP}$	--	--
GOE	32.146546 ft/sec^2	Earth constant

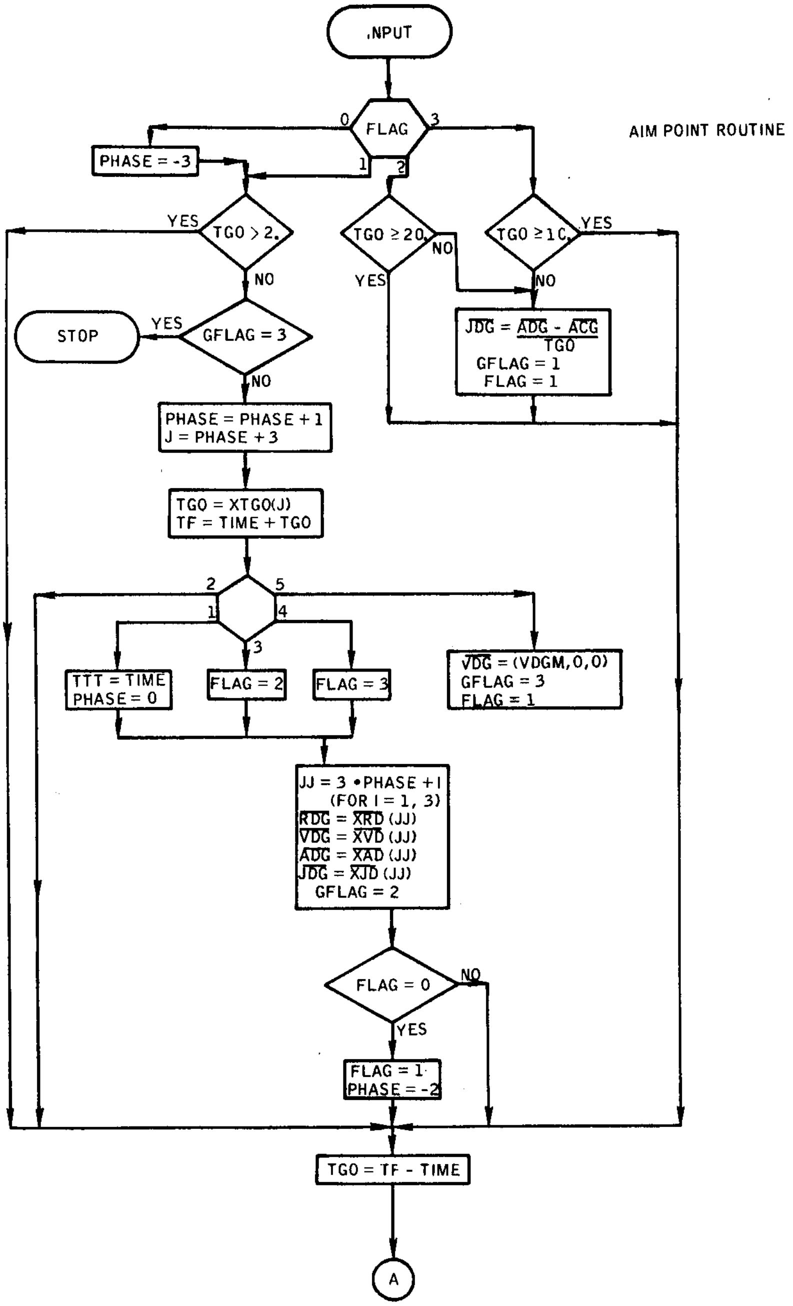
(e) Performance data

DELISP	2.8/410	
DELTHR	470/410	
THPC57	5985 lb	

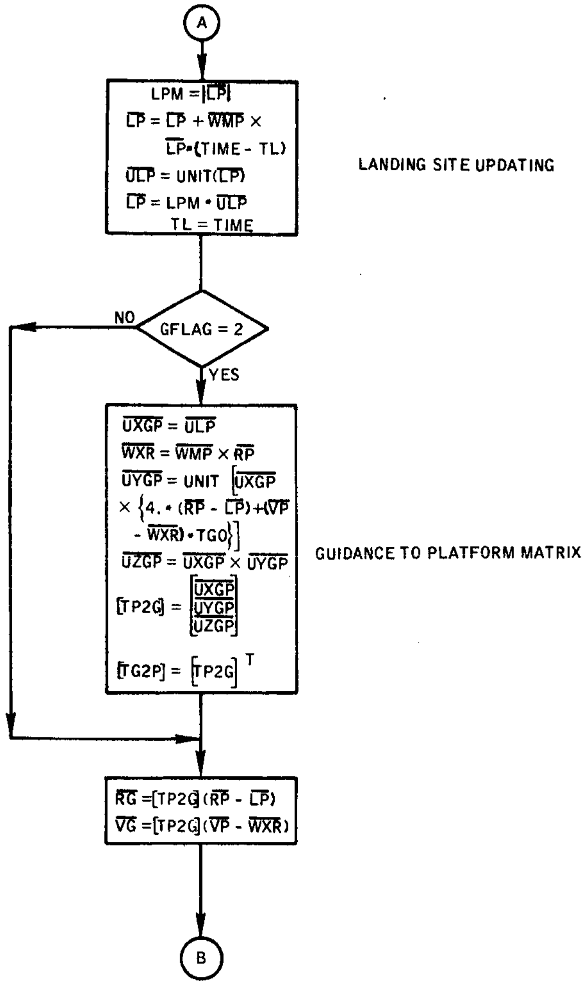
TABLE II.- REQUIRED INPUT - Concluded

(e) Performance data - Concluded

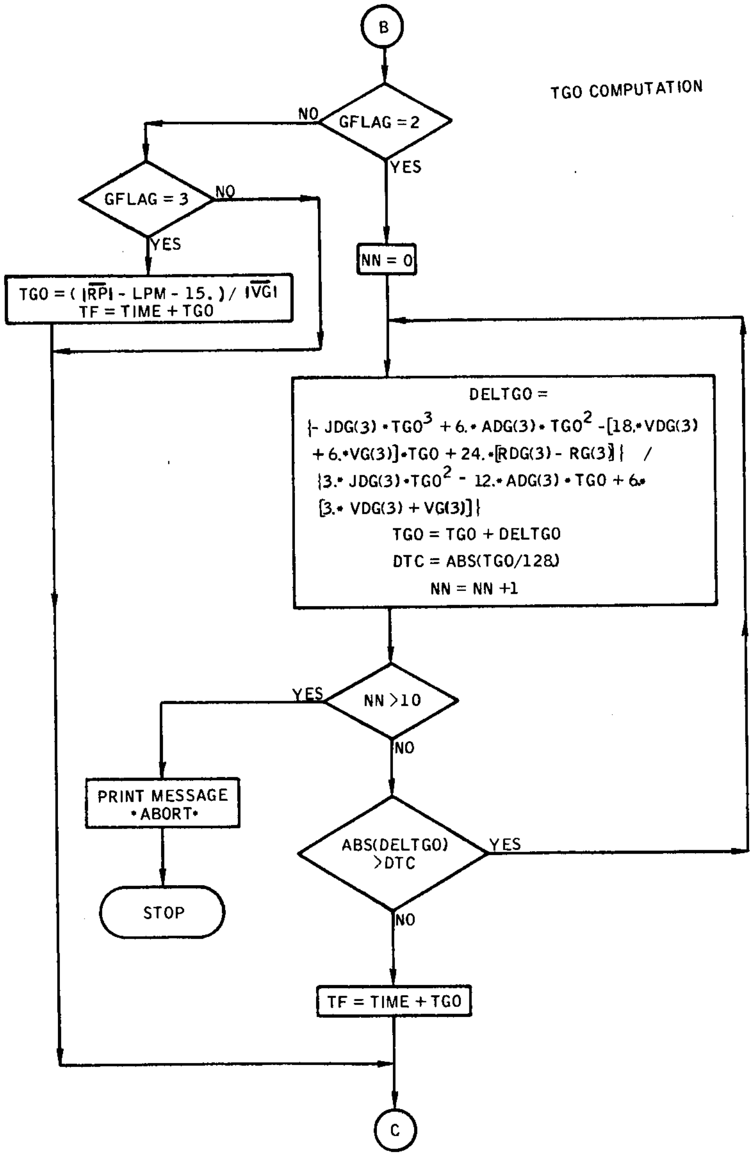
Symbol	Value	Definition
THPC63	6615 lb	
THRMAX	9710 lb	
THRMIN	1050 lb	
THRTRM	1050 lb	
THRUL	200 lb	
TRMISP	288 sec	
TRMT	26 sec	
ULISP	268 sec	
UT	7.5 sec	
WT	--	--
XISP0		To be supplied later
XISP1		
XISP2		
XISP3		
XKISP	306 sec	



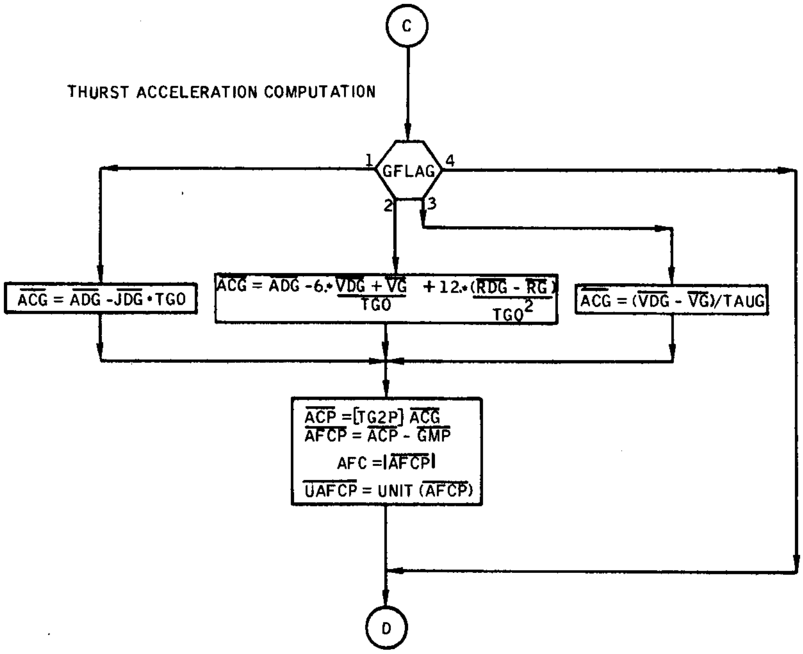
Flow chart 1.- Powered landing guidance.



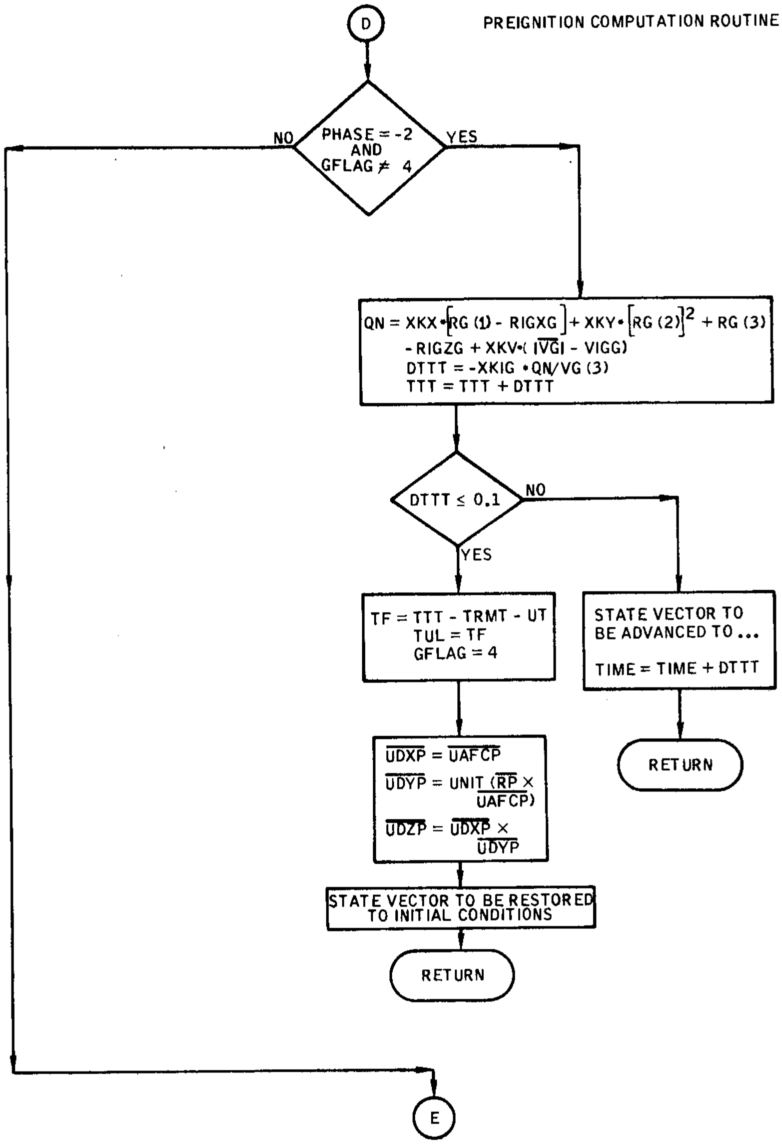
Flow chart 1.- Powered landing guidance - Continued.



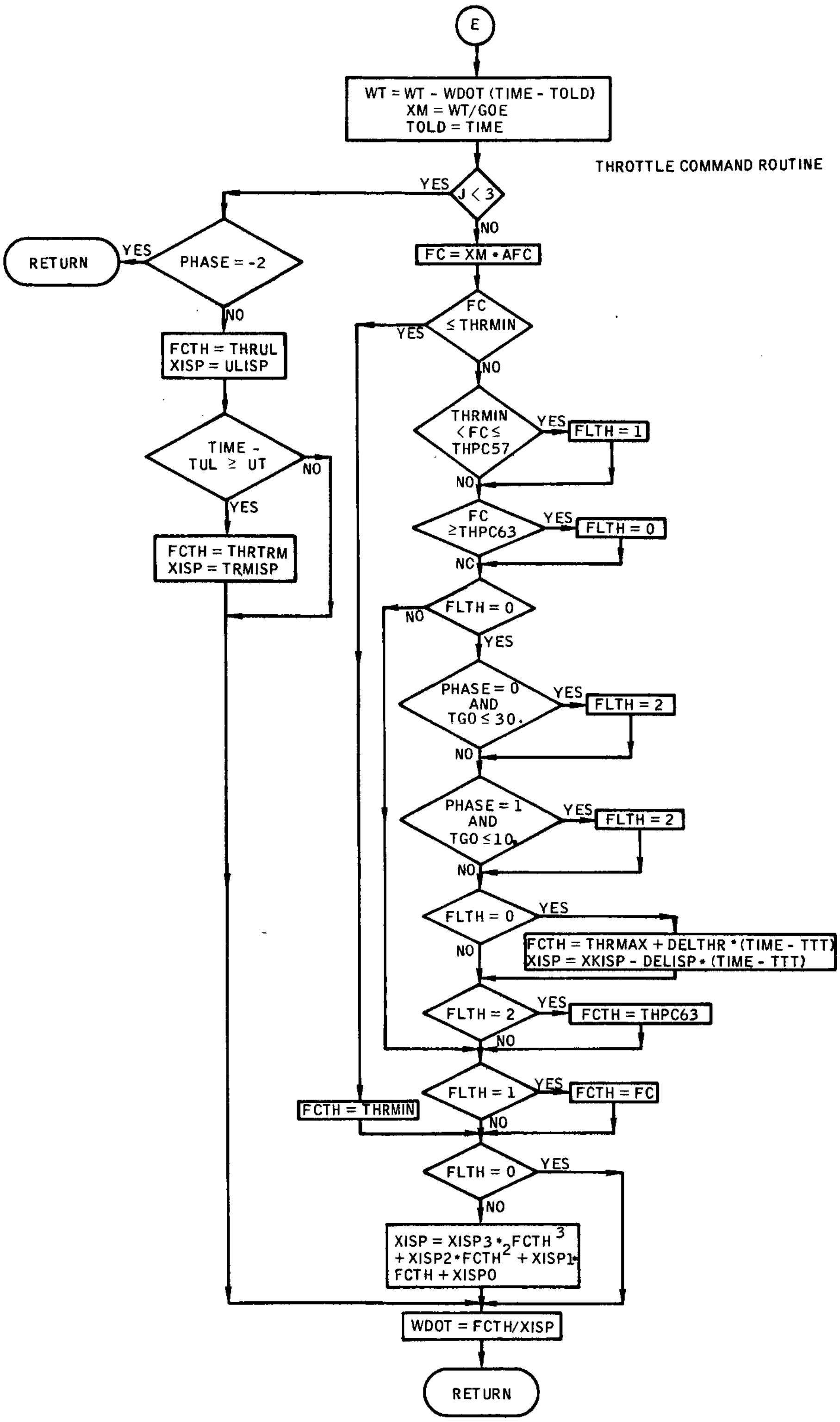
Flow chart 1.- Powered landing guidance - Continued.



Flow chart 1.- Powered landing guidance - Continued.



Flow chart 1.- Powered landing guidance - Continued.



Flow chart 1.- Powered landing guidance - Concluded.

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